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SPACECRAFT SECONDARY POWER REQUIREMENTS DURING THE SIXTIES

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SPACECRAFT SECONDARY POWER REQUIREMENTS DURING THE SIXTIES[1,2,3]

I. INTRODUCTION

Spacecraft secondary electrical power system provides all nonpropulsive power. This includes the requirements for guidance, attitude control, telemetry, and scientific experiments.

For secondary electrical power, not more than 3 to 5 kw will be required during the next five to eight years. This estimate is based on the availability of boosters and their payload weights as tabulated in Table 1.[4] As a general guide, 1/4 w/lb of spacecraft is the requirement. Figure 1 presents estimated minimum and maximum power needs during the 1960's.

For manned probes of the 60's it appears unlikely that more than 10 kw will be required for secondary electrical power. However, there is a developing need for high-power systems, such as 30 and 300 kw SNAP systems, for the testing of electrical propulsion devices. It is felt that these reactors should be developed and tailored

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[1]This paper presents the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under Contract NASw-6, sponsored by the National Aeronautics and Space Administration.

[2]This Technical Release was presented at the Conference on Electrical Engineering in Space Technology, sponsored by The American Institute of Electrical Engineers, in joint participation with The Institute of Radio Engineers and The American Rocket Society, at Dallas, Texas, April 11-13, 1960.

[3]The authors wish to emphasize that the ideas expressed herein are personal ones and are not necessarily those of the management at the Jet Propulsion Laboratory or the National Aeronautics and Space Administration.

[4]Table 1 of this Technical Release was taken from Space Handbook: Astronautics and its Applications, prepared by RAND Corp., Santa Monica, California.

to the electrical propulsion systems to which they will deliver more than 90 percent of their output. The relative amount of power requirements for communications, guidance, and life support will be negligible in comparison to the ultimate megawatt requirements for interplanetary electrical propulsion.

II. SPACE GOALS AND MISSIONS

The designer of electrical power systems must know the goals and purposes in space if he is to correctly make the many detailed design decisions that involve the trade-offs and compromises between the various technologies and the diverse objectives of the space program. As he attempts to resolve each technical question in electrical power system design he is quickly led, by a series of steps in logic, to the core question: "What should be the relative degree of emphasis on the development of technical equipment for lunar versus interplanetary flight operations?"

The authors believe that the general pattern of the exploration, the military operations, and the economic development of the North American continent will be repeated with respect to the development of operations in the solar system. Scientific exploration is the first phase; and it is a vital stepping stone that must, to some degree, precede manned operations in space. Manned operations in space will also be partially devoted to scientific exploration. The scientific exploration of space will probably uncover new knowledge, applicable to life on Earth, that may more than justify the cost of the entire space program. The development of new technology for space operations will probably lead to beneficial results on Earth, as from World War II operations radar fostered television and the atomic bomb led to peaceful uses of reactor power, plus the development of radio-isotope tracer research techniques in medicine.

In the development of the North American continent the initial phase of exploration was followed by military operations. The "scientific exploration" of Columbus was followed much later by the military operations of Cortez and La Salle. Although the idea of military operations in space is so repugnant that many avoid thinking about it, the technical advisors to our nation must face reality. If another nation is permitted to occupy and control the major bases in space such as the Moon, Mars, Venus, and others, America will lose her freedom to operate in space, except under a very substantial handicap. The struggle between France, England, and Spain in 1588 for the control of the North American continent is a lesson from history as to what the future may hold.

The third phase of development of new territory is that of economic or commercial operations. As Columbus could not foresee the economic development of the American continent, so it is difficult today to foresee in detail the economic development of space operations. However, given substantial amounts of electrical power to create whatever may be needed from the materials that already exist on the Moon and the planets, manned commercial operations in space will grow rapidly. At first there will be the service and housekeeping functions performed for a small laboratory staff. Later the servicing and maintenance of spacecraft will be conducted by commercial organizations. Logistics will dictate that - given unlimited power from nuclear reactors - ore reduction and machine shops will be established to make as many things as possible to establish self-sufficiency and reduce costs. Food will be grown by hydroponics.

The installed power-generating capacity on the Moon will grow rapidly and will probably exceed 500 Mw by 1985. As a matter of reference, the installed power-generating capacity of the United States exceeds 150,000 Mw.

There are many factors that affect the selection and design of the spacecraft electrical power system. In order to properly select a power system, a multiple-parameter matrix must be prepared. The following major factors are to be considered in this multiple-parameter matrix:

1. Objectives
2. Instrument or manned flight
3. Type of mission from a solar and energy storage standpoint
4. Propulsion or secondary power
5. Spacecraft weight
6. State of the art as it will develop in the future years

Table 2 presents a detailed breakdown of this power system parameter matrix.

The design of a spacecraft is a series of iterations, all iterations leading toward the most efficient and effective method of accomplishing the tasks. Preliminary descriptions of the operations of each of the various functions usually end up as a series of general statements. For example, a communication-functional specification might be written stating that the radiated RF power requirements were based upon required bandwidth, range, and possible antenna gain. Naturally, antenna pattern or gain is a direct function of the degree of attitude control achieved. An interaction also occurs between the desired scientific experiments, the possible methods of data storage, and the most efficient method of conversion to minimum bandwidth format. Attitude control and mechanization, primary Sun-orientation, or Earth-orientation of the spacecraft are problems which must be solved. Some of the various factors which concern these trade-offs will be discussed in the succeeding sections of the Technical Release.

III. DETAILED MISSIONS AND SUBSYSTEM ANALYSIS

Having established the mission and its objective, the trade-off between the power consumption for the various subsystems is made. Table 3 shows such a power system allocation chart for the first-generation JPL spacecraft. It is of interest to note that there are approximately 27 different voltages listed on this chart. Later analysis has indicated that the payload package will require an additional 20 different voltages. These power levels range from a few milliwatts to a maximum of 50 w. A block diagram of the experimental payload power system is shown in Fig. 2. This planned payload has an oriented solar-powered panel system with a non-rechargeable battery for launch-acquisition phases and as a subsequent back-up source of power. An over-all view of the spacecraft is shown in Fig. 3.

IV. SPACECRAFT SUBSYSTEMS POWER

A. Scientific Instruments

Figure 4 shows the manner in which the bandwidth compensation is utilized to transmit photographs of the Moon and the planets back to Earth. A 40,000-bit picture is transmitted in little over an hour with a 5 cps bandwidth system. For the early scientific Martian space probes, the scientists have determined that an 88-bit/sec bandwidth would transmit all the information considered necessary to obtain the desired scientific data. In space, the rate of change of scientific information is slow, and therefore large communication channel capacity is not required. It is not considered really necessary from a scientific standpoint to transmit television pictures in real time which would require a 6 mc bandwidth. Photographs can be taken at periodic intervals and the information transmitted continuously at a reduced bandwidth to lower the power requirements and still obtain very adequate scientific information. Seventy-eight bits/sec were similarly planned for the Venus space probe. Table 4 shows a tabulation of the scientific experiments planned and the bandwidth capacity requirements.

B. Communication Subsystem

It is possible to transmit a significant amount of information from the depths of space with a relatively small amount of power by utilizing the high-gain antennas of the world net and directional antenna aboard the spacecraft. Figure 5 shows a plot of the power requirements for a 100 cps bandwidth system in both the 100 and 1,000 Mc region.[5] As shown in Fig. 6, earth-oriented antennas of 25-ft diameter aboard the spacecraft will provide antenna gain of approximately 34 db at

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[5]Figure 5 of this Technical Release was taken from the Desklog of the Defense Electronics Division, General Electric Corporation, 1960 edition.

1,000 Mc. The world net antennas have a gain of approximately 60 db. It is therefore reasonable to plan on a transmission link in the 1960-1965 era of 90 db, as shown in Table 5. This permits the transmission, in 1964, of a very significant amount of scientific information for slightly more than 100 w of transmitter power. Transmitter power efficiency is usually 25 to 35 percent.

Utilizing the world net, it is apparent as shown in Table 5 that a 100 w transmitter with a power input of 300 w will be able to transmit television pictures in real time from the Moon in 1964. Voice conversations in real time from Mars and Venus will be readily possible by 1964. Those communications systems described in Table 5 utilize no data processing to eliminate redundant information and increase the efficiency of the transmitter system. No bandwidth compensation techniques are considered in the data presented in Table 5. Very substantial gains - a factor of three - could be achieved in the transmission of information in terms of bits per watt if these advanced communication techniques were utilized.

The significance of the signal-to-noise ratio is graphically demonstrated in Fig. 7 and 8 which present photographs of the Moon at both 10 and 20 db signal-to-noise ratios.[6]

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[6]Figures 7 and 8 of this Technical Release were obtained from "Pictorial Data Transmission From a Space Vehicle" by J. F. Baumunk and S. H. Roth, an article published in Electrical Engineering Magazine, Vol. 79, No. 2, pp. 134-138, February, 1960.

In summary it should be recognized that one cannot discuss the power requirements of various space radio-communications systems unless the following factors are carefully specified:

1. Antenna gain, both on the ground and on the spacecraft
2. Signal-to-noise ratio
3. Bandwidth
4. Transmission frequency
5. Utilization of various incoding, data processing, and bandwidth compensation techniques

It has been shown that 350 w of electrical power is adequate for the power requirements during the 1960 - 1965 era for intelligently designed radio communications systems.

C. Guidance and Control Subsystem

The power requirements for the guidance and control systems envisaged for the 1960 - 1965 era will not exceed 1/2 to 3/4 kw. Space-stabilized platforms require approximately 350 w; attitude control systems utilize no more than 75 w. The average power drawn by actuators in space is negligible because they have only to overcome stictions and inertia. The requirements for telemetry data processing systems do not exceed more than 10 w. The requirements for data storage and spacecraft computer operation are not expected to exceed 100 w during the 1960-1965 era. Of course, all these electronic systems incorporate transistors for reliability reasons.

The area of guidance and control represents an outstanding example of the nature of some of the trade-offs possible in the design of the spacecraft power system. Because inertia is the only major reaction torque in the attitude control of the spacecraft, and because the minimum spacecraft flight time is approximately 40 hr, it is quite possible to conserve power by limiting the rate of the maneuvers. Maneuvers which normally require less than a minute in the guided missile will require one-half to one hour in the spacecraft. This reduction in the required time of maneuver results in the lessening of the power demand, as indicated above.

D. Equipment Environmental Control Subsystem

It has been demonstrated that the temperature of spacecraft can be maintained at a confortable room temperature of 70°F, ±20°F, with either static or dynamic heat-balance systems that require essentially no power. Systems that incorporate variable black-white area radiators that are operated by bi-metallic elements and require no electrical power have been successfully used in space flights. Flights have been made in which the black-white areas have been previously determined by analysis and fixed for stellar flight. The thermal lag and storage characteristics were such that the temperature did not vary more than ±20°F from room temperature during each satellite orbit.

Internal heat control of the various components of the spacecraft is another problem which will require close analysis. Because of the lack of gravity it is necessary to eliminate convection as a cooling mechanism and consideration must be given to methods of assuring adequate heat transfer by conductive methods only. In more sophisticated spacecraft approximately 50 w of power may well be required to circulate a cooling medium and insure adequate heat transfer to space radiators.

E. Life Support Systems

The power requirements of the early manned space flight systems will be 60 w for the life support system. This power is required to operate fans, and to remove moisture from the air passing over the astronauts during their planned 30-hour flight. For flights of approximately 100 to 150 days, preliminary analysis shows that the lighter weight systems are those in which food and oxygen make-up is carried along. The power requirements for these systems are relatively small. For operations in excess of 100 to 150 days algae systems are under development which would be utilized to replace the carbon dioxide in the air breathed by man and to grow food for his consumption. If electric lights were used to illuminate the algae, 6 kw of power would be required per man. However, it is recognizable that large amounts of solar power could be utilized to illuminate the algae directly. Approximately two and one-half square meters of surface per man would be required, and a few watts of power to pump the algae around in the solar-illuminated structures. Figure 9 and Tables 6 and 7 show, respectively, a block diagram for a quartz-lamp-illuminated algae system, and a power analysis of a comparable system.[7,8]

As discussed in Section D above, no power would be required to maintain a comfortable temperature for the astronauts, for flights in the solar system that did not go out beyond Mars. While a spacecraft is in the Sun, of course, no power is required for illumination to observe or record data; while in the shadow, a 14-w fluorescent lamp would be adequate to provide illumination for each man.

F. Surface Propulsion Subsystem

For surface propulsion on the Moon or the planets, it is estimated that from 1/3 to 1 hp would be required to propel small instrument tractors over the surface at reasonable speeds. Mission analysis has shown that 10 w of electrical power would be adequate for initial stationary scientific probes.

G. Summary

A summary of the secondary electrical power required during the 1960 - 1965 period for a typical spacecraft is shown in Table 8. For manned probes

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[7] Figure 9 of this Technical Release was presented in a paper, "Closed-Cycle Air Purification With Algae" by D. Burke, G. Hobby, and T. Gaucher of General Dynamics Corporation, at the First International Naval Symposium of Submarine and Space Medicine, held at the United States Naval Submarine Base, New London, Connecticut, September 12, 1958.

[8] Tables 6 and 7 of this Technical Release were obtained from "Basic Remarks on the Use of Plants as Biological Gas Exchangers" by J. Meyers, an article published in The Journal of Aviation Medicine, Vol. 25, pp. 407-411, 1954.

the power requirements are not estimated to exceed a kilowatt or a few kilowatts at most, perhaps 1 to 3 kw.

V. POWER SOURCES

It is not the purpose of this paper to review the various solar, nuclear, and chemical sources for space applications. This subject has been adequately covered in other papers. The Jet Propulsion Laboratory has devoted considerable attention to the application of solar cells for missions in the near future. A chart showing the characteristics of these solar panels to Earth, Mars, and Venus is shown in Table 9. For the future, the reactor-powered thermo-electric converter known as SNAP-10 which provides 200 to 300 electrical watts, and is shown conceptually in Fig. 10, appears very attractive for some missions.[9] The development of more rugged fuel cells for energy storage applications for satellites and surface operations is proceeding, and will be needed during the sixties.

VI. SUMMARY

It has been shown above that no more than 3 kw of electrical power will be required for the secondary electrical power systems during the 1960 - 1965 period. Higher-powered systems, such as the 30 kw SNAP-VIII, are being developed and are required for the testing in space of electric propulsion motors.

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[9]Figure 10 of this Technical Release was taken from "Nuclear Thermo-electric Power Supply," by R. J. Harvey, of Martin Aircraft Corporation, Baltimore, Maryland, which was presented as Paper No. 59-911 at the Conference of the American Institute of Electrical Engineers, Seattle, Washington, June 21-26, 1959.

Within 15 years, megawatts of electrical power will be required for interplanetary electrical propulsion, and for permanent manned bases on the Moon and the planets.

Table 1. Summary of current and expected payload-weight capabilities.

Item	Vanguard	Jupiter C	Thor/ Jupiter	Atlas/ Titan	Saturn	
Weight, lb[a]	22,000	40,000-50,000	100,000	200,000		
Thrust	28,000	75,000	150,000	300,000	1,500,000	3,000,000
300-mi. Satellite	20	15-30	100-2,000	2,000-8,000	37,000	75,000
22,400-mi. (24-hr) Stationary Satellite			25-600	500-2,500	11,000	22,000
Moon Impact (Circumlunar)			50-800	600-3,000	13,000	25,000
Moon Satellite			15-500	300-1,500	6,000	13,000
Moon Landing			10-300	200-1,000	4,000	8,000
Venus/Mars Flight			25-600	500-2,500	12,000	23,000
Jupiter Flight			10-400	300-1,500	2,500	5,000

[a]All units shown in lb.

Table 2. Space electrical power systems parameter matrix.

1. OBJECTIVES

   1.1 Scientific Exploration
   1.2 Military Operations
   1.3 Commercial Operations

2. INSTRUMENT OR MANNED OPERATION

   2.1 Instrument
   2.2 Manned

3. TYPE OF MISSION RE SOLAR AND ENERGY STORAGE

   3.1 Space Flight Continuously in Sun
   3.2 Satellite Requiring Energy Storage
   3.3 Surface Operations
      a. Period of shadow operation
      b. Surface propulsion power
      c. Permanent manned base

4. PROPULSION OR SECONDARY ELECTRICAL POWER SYSTEM

   4.1 Propulsion
   4.2 Secondary

5. SPACECRAFT WEIGHT

   5.1 Under 100 lbs
   5.2 100 - 1000 lbs
   5.3 1000 - 10,000 lbs
   5.4 10,000 - 100,000 lbs
   5.5 100,000 - 1,000,000 lbs

6. STATE OF THE ART AS IT WILL DEVELOP IN THE FUTURE

   6.1 1960-1965
   6.2 1965-1970
   6.3 1970-1975
   6.4 1975-1980
   6.5 1980-1985

Table 3. Typical Early 1960 Spacecraft Power Allocation

Spacecraft Power Analysis, Revised January 20, 1960

Static Converter Name	Application	Input,[a] w Average	Estimated Efficiency	Volts Out	Deviation %	Frequency	Output, w Average
Communications	1/4 w Transmitter	From Separate 80-hr Battery, 4 w	66	-12 + 4.75 +100	±5 ±2 ±2	DC DC DC	0.84 0.95 0.83
	Transponder	11.7	68	+20 -20	±5 ±5	DC DC	6.0 1.92
	1/4 w Power Amplifier	4.4	68	+ 4.75 +100	±2 ±2	DC DC	2.38 0.6
	3 w	12.3	68	+ 4.75 +275	±2 ±2	DC DC	2.38 6.0
May be Eliminated Officially in the Near Future	10 w	22. 42.[b]	68 68	+ 4.75 +275 +500	±2 ±2 ±2	DC DC DC	14.25 0.83 28.57
Attitude Control		Acquire[c] 39. Cruise 23.	67	+26 -26 26 700 20	±5 ±5 ±5 ±5 ±5	DC DC 400 1554 1554	13.7 0.7 11.0 1.5 1.0
Data Encoder (Engineering Telemetering) and Command Decoder	Engineering Telemetering Command Decoder	11. .71 1.5 5.	70	31 - 23 -20 31 - 23 31 - 23	Raw Power ±2.5 Raw Power Raw Power	DC DC DC DC	0.5
Controller Timer		3.1 3.9	67	26 +26 -26 31 - 23	±5 ±5 ±5 Raw Power	400 DC DC DC	0.052 1.04 1.04 3.9
Scientific Packages		7.1	85	28 28	±5 ±5	2400 2400	3. 3.
		Acquire 163.71 2 hr Cruise 147.7	← Total →				Cruise 105.98

[a]Input Voltage 31 - 23

[b]8.3 w During Launch - 17 min

[c]21 w During Launch - 17 min

Table 4. Summary of data transmitted to Earth from a family of payloads.

Experiment	Sampling Rate	Duration of Sample	Info/Sample (bits/sample)	Info Rate (bits/sec)	Duration of Experiment	Experiment Performed	Digital or Analog	Requirements
Optical System	1 hr 55 min[a]	5 to 10 min	6,000	1	6 days 8 hr	Venus, Mars ±3 days Moon ±4 hr	D[a]	Coding
Cosmic Ray 1) Pulse Chamber	Continuous	2 min sweep	25,000	15	0 to 124 days	Venus, Lunar	D	2 instruments, 2 channels, scaling (may be similar to Pioneer II fast counting system)
2) Integrating Chamber	5 sec to 2 hr	3 sec	1	0.5	0 to 124 days	Venus, Lunar	D	Superimpose on one of above channels
3) Geiger-Mueller Tube	Continuous	-	-	0.17	0 to 180 days	Mars	D	Scaling circuits, 1 channel, info rate may be reduced more if necessary
Magnetic Field	0.5 sec	0.2 sec	7	21	0 to 124 days	Venus, Lunar	D	Number of channels and whether binary not known
Micrometeorite	6 hr	6 hr	22	22	0 to 124 days	Venus, Lunar	D	Scaler, 1 sq ft assumed, sampling rate and info. rate are tentative
Meteor Detector	-	-	1	1	0 to 124 days	Mars, Venus, Lunar	D	
Solar Corpuscular Radiation	Continuous	1 min sweep	1	1 (5 cps bandwidth)	0 to 124 days	Venus, Lunar	A[c]	1 channel, probably in-flight calibration, based on 10 db S/N
Passive Radar	1 hr 55 min	5 to 10 min	6,000	1	6 days 3 hr	Venus ±3 days Moon ±4 hr	D	Coding
Photography	1 hr 10 min	0.01 sec	40,000	10 (5 cps bandwidth)	6 days 8 hr	Mars ±3 days Moon ±4 hr	A	200 line, ~ 6 shades of grey minimum 10 db S/N, 2 second recording time
Gamma-Ray Spectrography								
Solar Ionosphere	-	-	-	-	-	After Venus passage After Lunar passage		Continuous transmitting using solar power as long as possible

[a]Alternating sampling when operated with passive radar.

[b]Possible use of an analog system is being considered.

[c]A digital system is being studied.

Table 5. Deep-space net long-term capability predicted schedule

Characteristic	1960	1962	1964	1966	1968
Transmitter Power, radiated					
ground	10 kw	10 kw	10 kw	100 kw	100 kw
spacecraft	10 w	25 w	100 w	1 kw	1 kw
Antenna Gain					
ground	46 db	46 db	54 db	64 db	64 db
spacecraft	6 db	20 db	30 db	30 db	40 db
Receiver Sensitivity					
ground	300°K	100°K	40°K	40°K	20°K
spacecraft	2000°K	2000°K	400°K	400°K	400°K
Information Bandwidth--Telemetry (10 db S/N)					
satellite application	3.5 kc	1 mc	1-10 mc	1-10 mc	1-10 mc
lunar application	3.5 kc	1 mc	1-10 mc	1-10 mc	1-10 mc
Mars application		100 cps 18 db S/N	10 kc	1 mc	1-2 mc
Venus application		400 cps 18 db S/N	40 kc	1-4 mc	1-8 mc
edge of solar system			10 cps	1 kc	2 kc

Table 6. Power requirements of an algal gas exchanger (Tentative Estimate)
Unit: hp = 640 kcal/hr

Item	Efficiency %
Demand: 1 man-unit at 120 kcal/hr = 0.19 hp	
Conversion, electrical to light, efficiency:	
For fluorescent lamp (highest available):	0.19
Conversion, light to ($CO_2 \rightarrow O_2$), efficiency:	
Maximum observed:	0.30-0.65
Maximum observed, steady-state growth:	0.24
Considered reasonably obtainable:	0.10
Over-all efficiency: 0.10 x 0.19 = 0.019	
Power requirement: 0.19 hp/0.019 eff = 10 hp/man	
References[2,6,7]	

Table 7. Expended and produced materials of an algal gas exchanger

Characteristic
Basis: 1 man unit = 2.3 kg algae growing at 1/2 maximum rate or 4% per hour increase; 92 gm fresh weight, or 23 gm dry weight/hr
Mineral salt requirement: at ash content 5% = 1.2 gm salt/man-hr
Nitrogen requirement: at 8% N = 1.8 gm N/man-hr equivalent to 2.2 gm NH_3 or 3.9 gm urea/man-hr

Table 8. Spacecraft secondary electrical power required for 1960 - 1965.

Subsystem	Description	Minimum Power w	Maximum Power w
Scientific instruments	Seismometer, cosmic ray, Lyman-Alpha	10	100
Radio communication	1,000 mc 85 ft ground antenna 25 ft spacecraft antenna no information processing	5	300
Guidance and control	Includes space inertial platform, computer, attitude control, and autopilot	35	400
Actuator average power		1	10
Data encoding and telemetry		5	100
	Sub-total - instrument probes	56	910
Life support/man[1]		0	6000/man
	manned spacecraft	56	910 +6000/man

[1]Manned space flight for missions of more than 100 days that may require 6 kw of electrical power to grow algae for food and to exchange carbon dioxide for oxygen will probably not occur until after 1970.

Table 9. Regulated solar power performance

Characteristic	Venus	Earth	Mars
Total solar panel area - m^2	4.98	4.98	4.98
Effective area - 85% coverage - m^2	4.24	4.24	4.24
Sun distance in 10^6 mi	67.3	92.8	141.7
Solar power above atmosphere - w/m^2	2685	1400	605
Photo - voltaic efficiency at 25°C - %	6.86[a]	6.86[a]	6.86[a]
Photo - voltaic temperature[b] - °C	+97	+39	-21
Photo - voltaic efficiency at operating temperature - %	4.42	6.39	8.0[c]
Power per sq m at 85% coverage - w	102	76	41.1
Total solar panel output - w (6 panels)	503	378	205
Regulated solar power at 70% efficiency - w	352	265	143.5
Regulated power output with estimated 5% loss due to series - parallel mismatch - w	334	252	136

[a]6.86% efficiency is based on solar power above Earth's atmosphere where efficiency is lower than at the Earth's surface.

[b]Cell temperature calculations assume that the solar panel is thermally alone in space and emissivity used includes the effect of the glass slide, and the anti-reflection coating and the ultra-violet reflecting coating.

[c]Assumes optimum impedance match at -21°C.

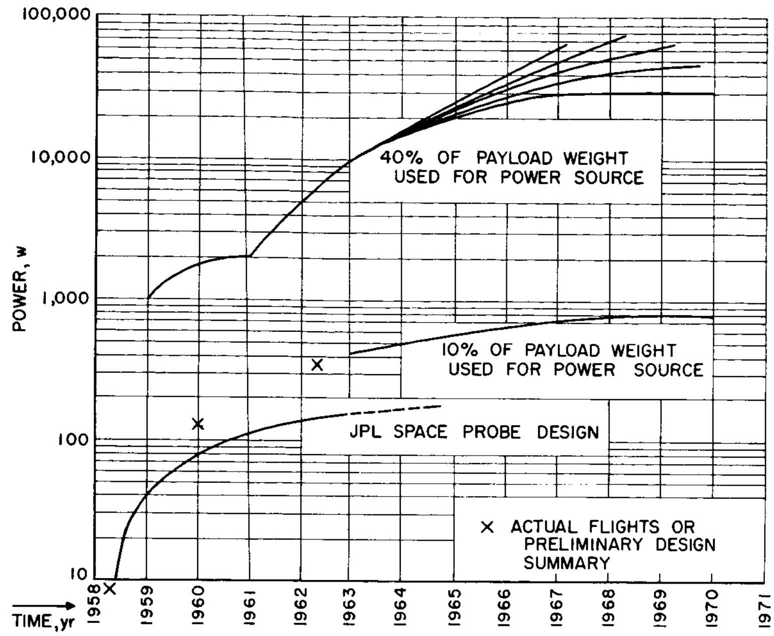

Fig. 1. Estimated power demand vs time.

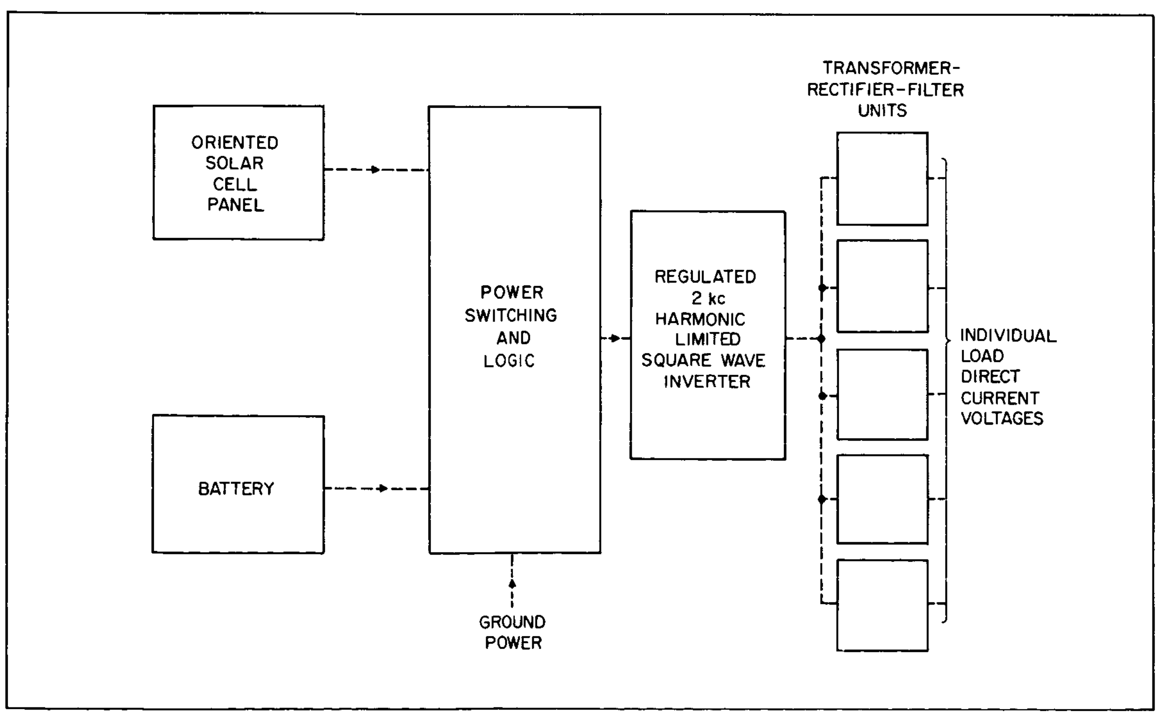

Fig. 2. Spacecraft electrical power system.

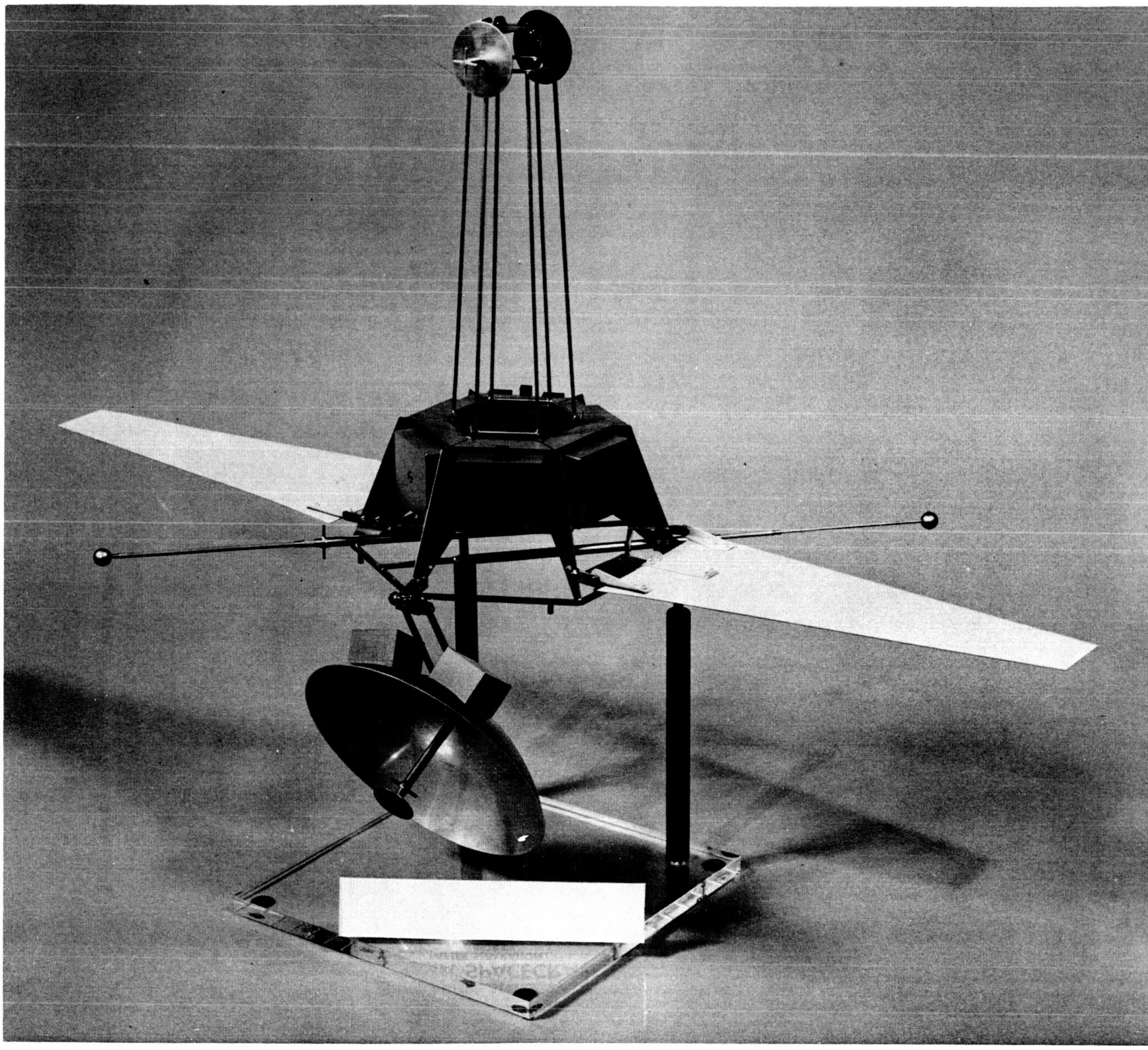

Fig. 3. Over-all view of early 1960 spacecraft.

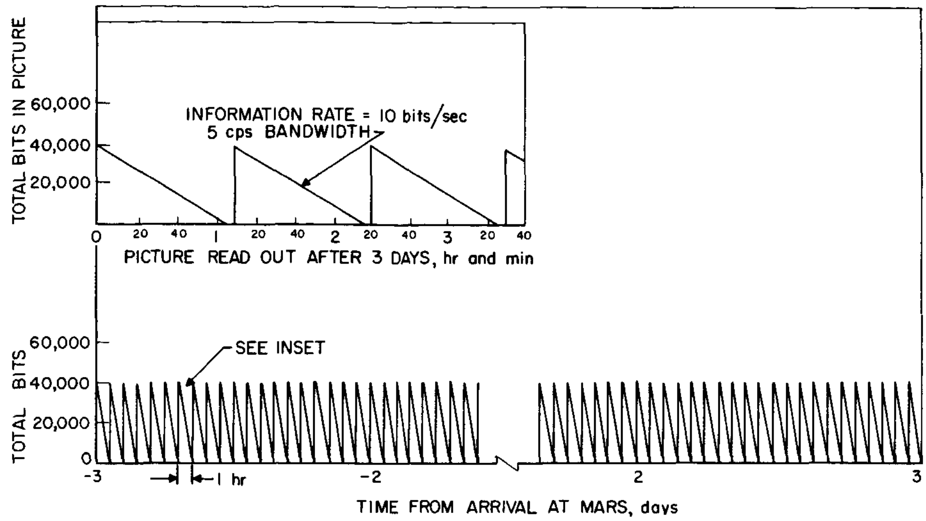

Fig. 4. Photographic bandwidth compression.

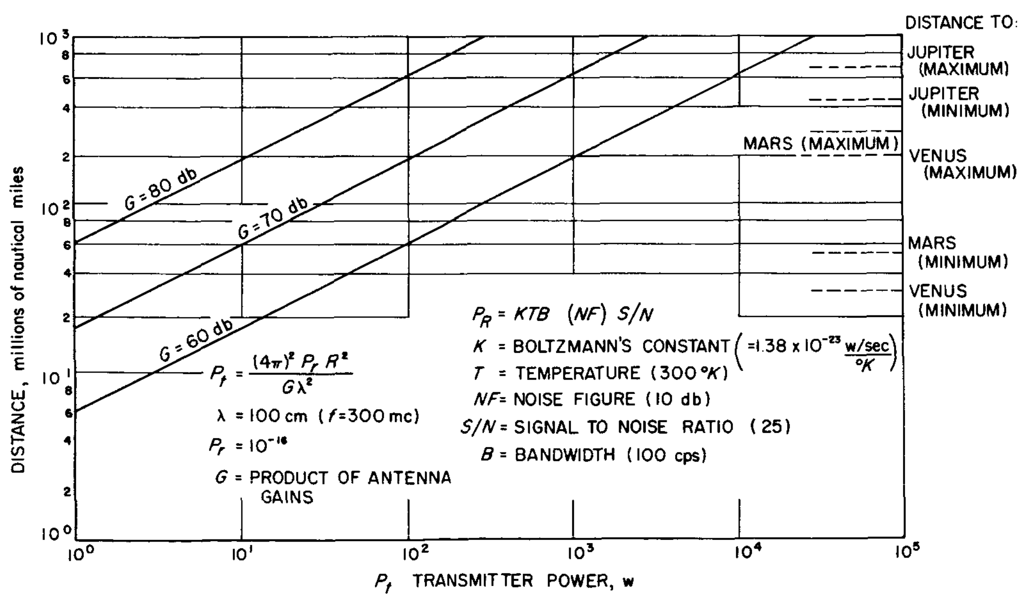

Fig. 5. Radio transmitter power vs range.

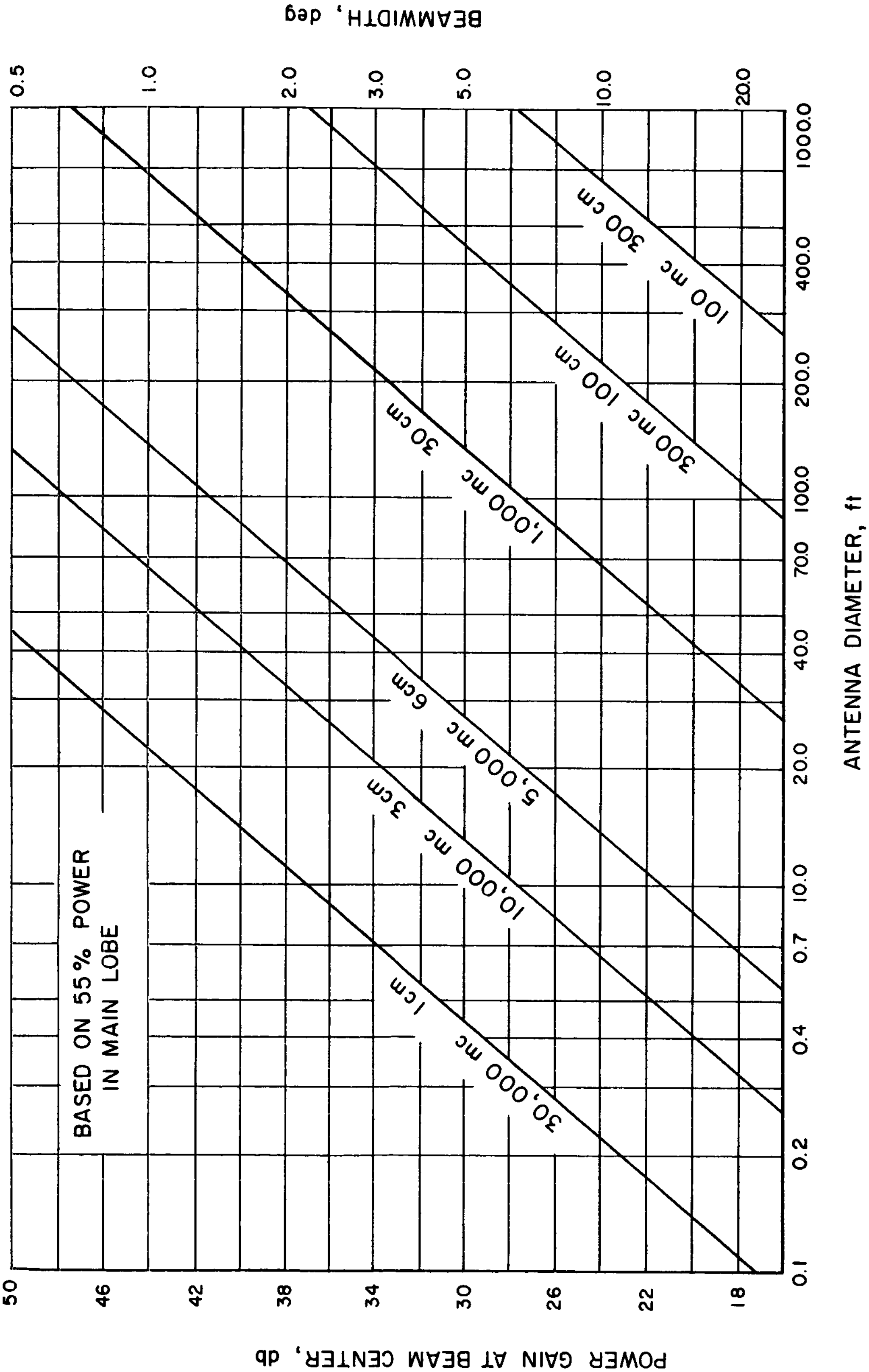

Fig. 6. Gain and beamwidth of circular parabolic reflectors.

Fig. 7. Lunar photograph, 10 db signal/noise ratio.

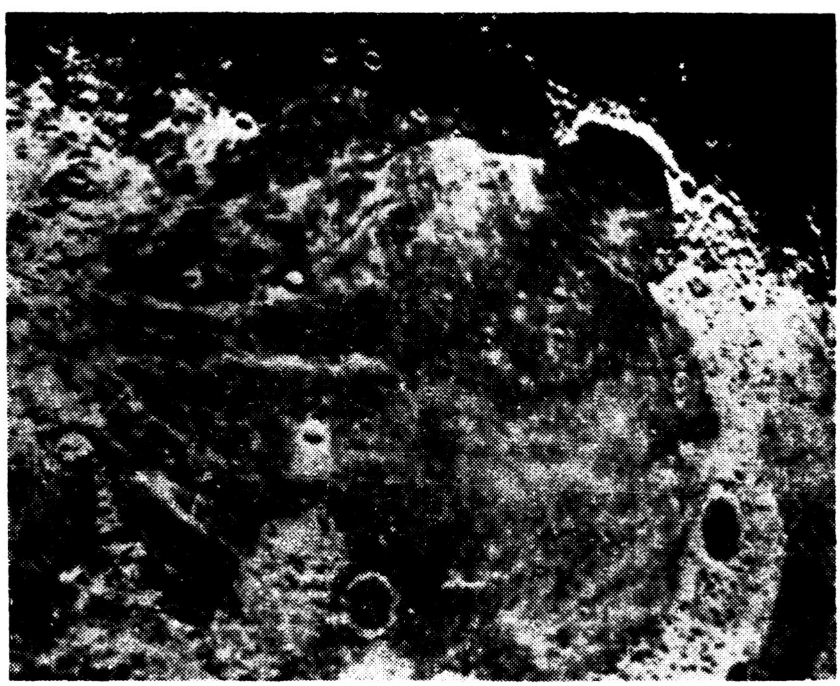

Fig. 8. Lunar photograph, 20 db signal/noise ratio.

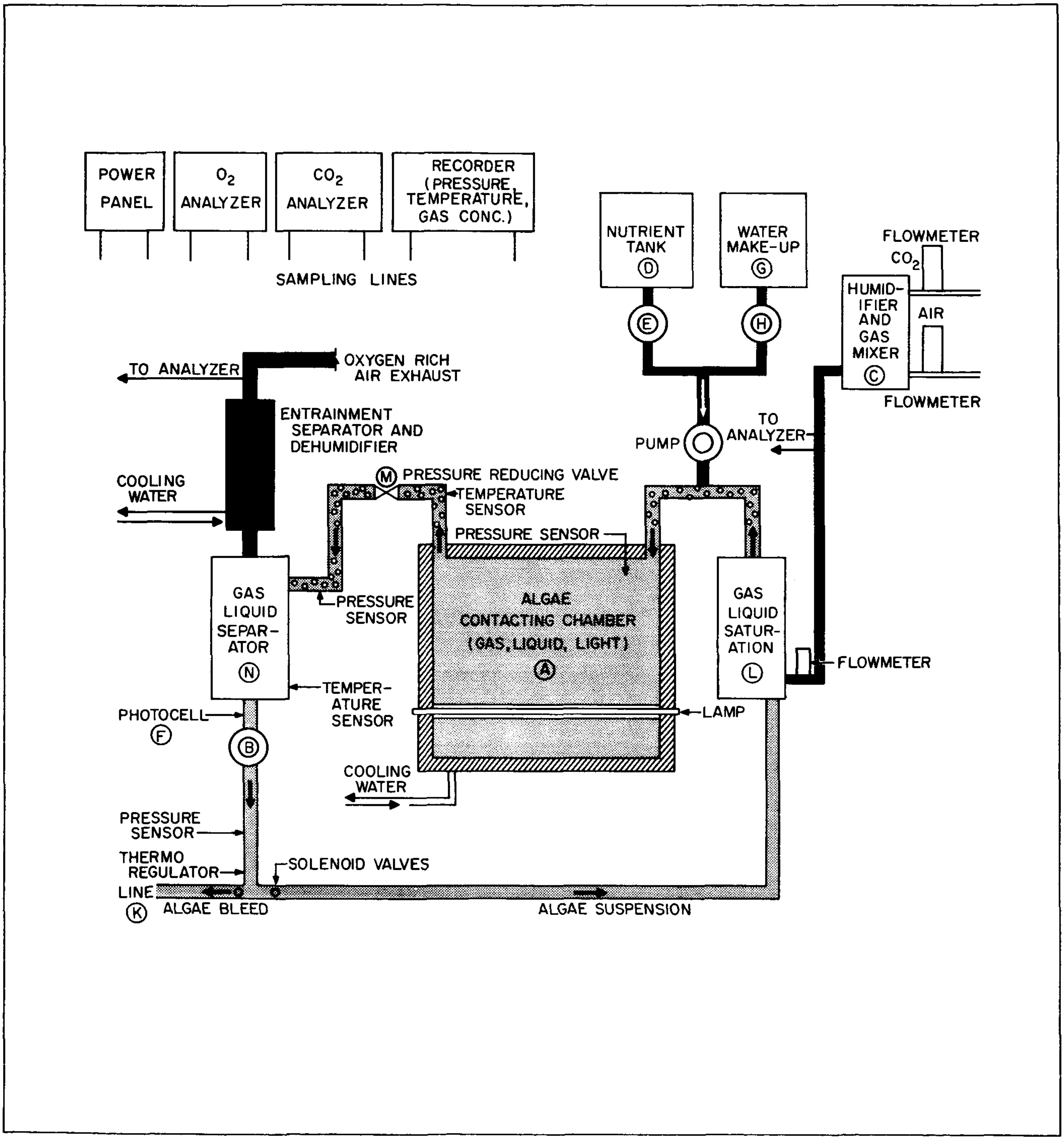

Fig. 9. Qualitative flow diagram of photosynthetic gas exchanger.

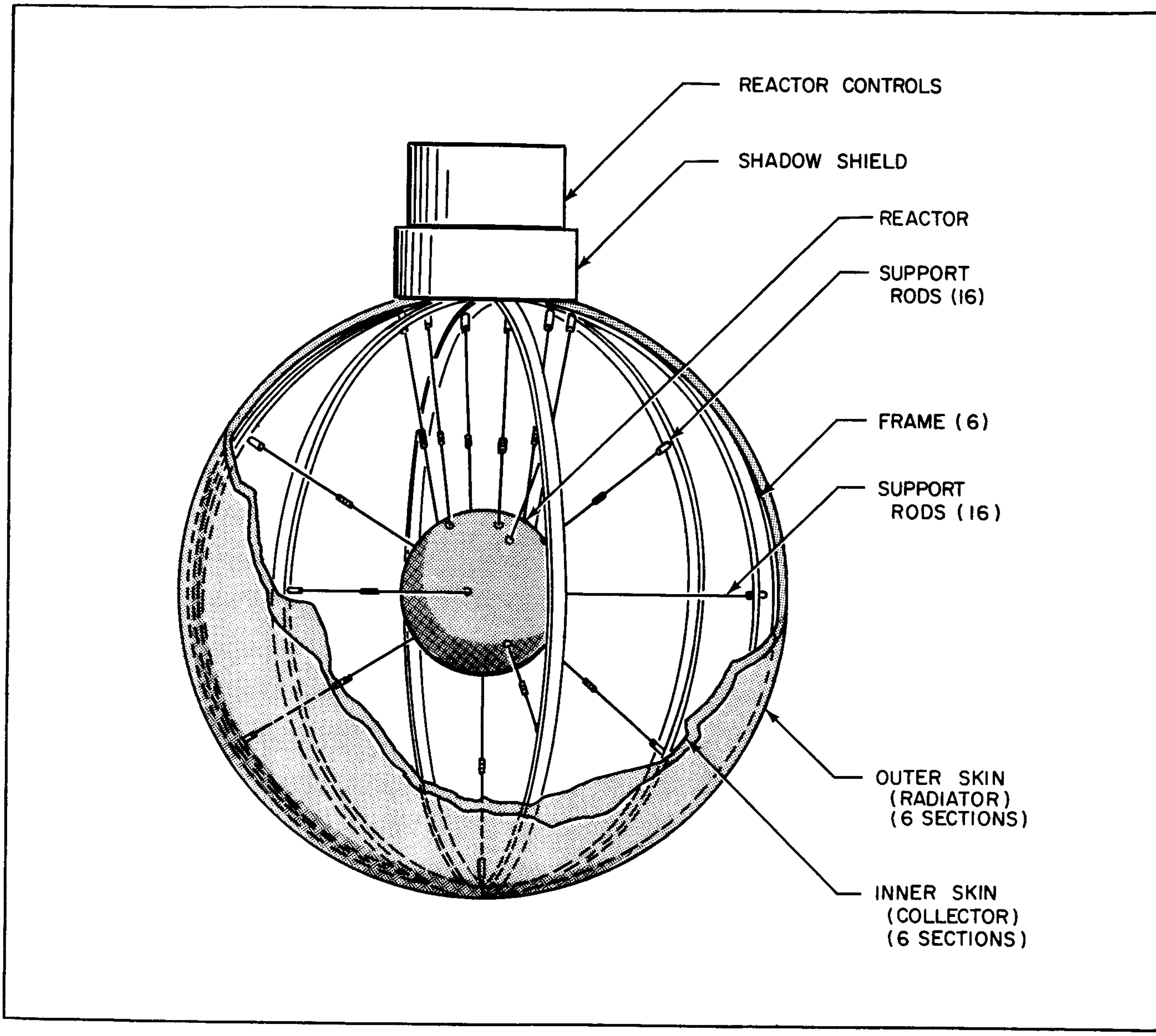

Fig. 10. Thermoelectric device, isometric view.